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Ultra MLC Technology Introduction

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1. Introduction

Flash memory is a non-volatile storage element that can be electrically programmed/re-programmed and erased. As technology continuously advances, the demands for greater density and better performance with flash memory become large as well. Most importantly, flash memory is no longer a component that resides only in your computer – It could act as a photo album or a file cabinet that stores all your personal treasures or business portfolios.

The purpose of this paper is to provide an overview on flash technology, specifically on NAND flash, a memory technology that has been deeply connected to our day-to-day life. In addition, we would like to introduce another MLC flash member, Ultra MLC, which delivers better performance and endurance – just like the legendary SLC flash.

The paper is organized as follows: Section 2 explains the differences between NAND and NOR flash, and provides information on NAND flash including SLC and MLC. Section 3 introduces Ultra MLC – the mechanism and its advantages. Section 4 and 5 provide performance and endurance information with Ultra MLC, respectively. Finally, a conclusion is provided.

2. Flash Memory

a. Physical Structure

NAND and NOR are the types of flash memory, commonly taken side-by-side for comparison due to their nature in data storing. To distinguish their differences, one could think that NOR flash is used for code storage whereas NAND flash is used for file storage.

The reason for such a differentiation comes from the fact that NOR flash is capable of achieving fast random access and performing fast read operations, but is restricted by slower write and erase operations. Therefore, NOR flash is more suitable for infrequent data modification, and it is common to see that boot code, firmware or operating system to be stored in NOR flash.

On the other hand, NAND flash is capable of performing fast write and erase operations. It also consumes less layout area, which could be translated to greater density and lower cost-per-bit. Almost as good as it sounds, NAND flash has one thing that is unable to outperform NOR flash: That is, slower random access, as the trade off to space saving. Nevertheless, NAND flash is still widely used in various types of file storage elements such as USB flash drives and memory cards, where data constantly needs to be loaded and updated.

Figure 1 represents the physical differences between NOR and NAND flash. The NOR structure (Left) is designed to connect each memory cell (highlighted in yellow) vertically, whereas the NAND structure (Right) is designed to connect each memory cell (highlighted in yellow) horizontally. 10F2 and 4F2 represent the layout area per cell for NOR and NAND, respectively. As we mentioned before, NAND flash requires less layout-area consumption and therefore delivers a wider range of capacities and lower bit-cost.

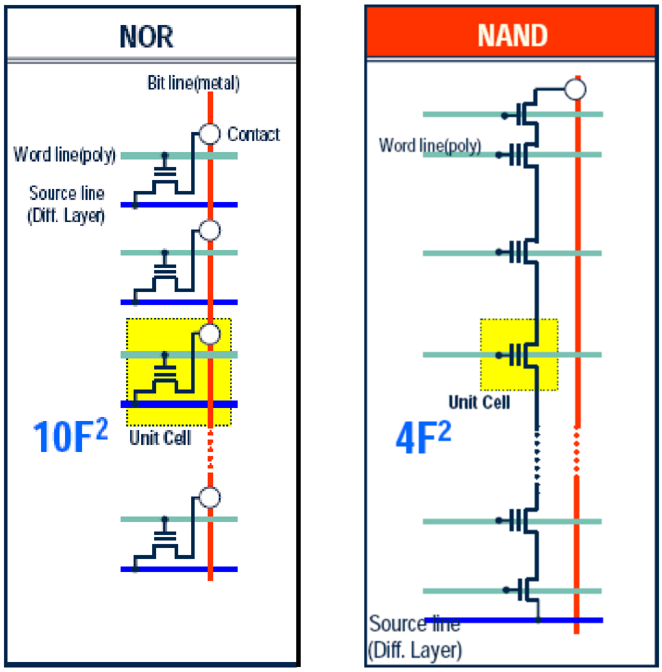

Figure 1: (Left) Cell Array for NOR and (Right) Cell Array for NAND

In the rest of the paper, we will focus on NAND flash and introduce Phison's unique design of ultra MLC including its mechanism, performance and endurance.

b. Types of NAND Flash

Generally, NAND flash is categorized in two types – SLC (single-level cell) and MLC (multi-level cell). NAND-makers have recently announced the latest flash technology - TLC (ternary-level cell), also known as three-bit per cell, which is the new addition to the NAND family. However, it is beyond the scope of our topic, and will not be covered in the paper.

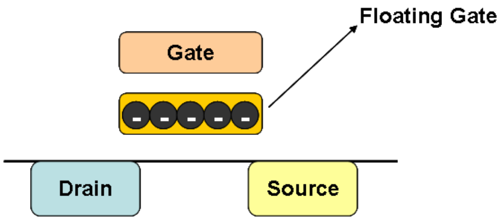

Figure 2: Basic Structure of a Memory Cell

Each cell is consisted of a single transistor and a floating gate, which is located between Gate and Source/Drain and allows electrons to be stored inside, as shown in Figure 2. For SLC flash, only one bit could be stored to each cell at a time, and there will be two possible states for each cell – 0 or 1. As for MLC flash, two bits could be stored to each cell at a time and there will be four possible states for each cell – 00, 01, 10 or 11. Cell state is determined by the threshold voltage (Vt) of each cell, and the voltage is an interpretation of the amount of charges stored inside the floating gate, as shown in Figure 3.

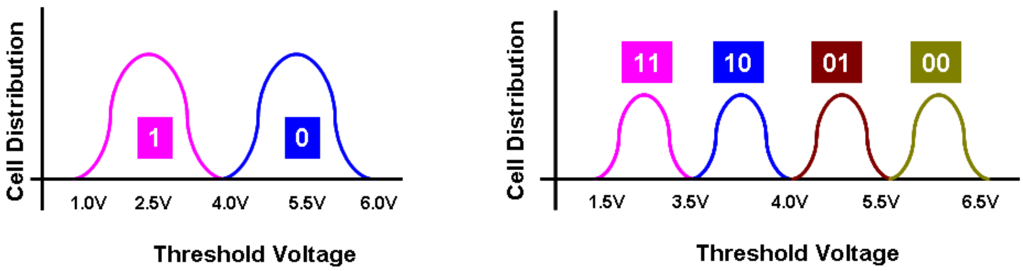

Figure 3: Cell Distribution vs. Threshold Voltage for SLC Flash (Left) and MLC Flash (Right), Respectively

Because MLC flash stores 1 more bit at each cell than SLC flash does, MLC provides higher density and lower bit-cost. Unfortunately, nothing comes for free – the trade off for cost-saving is greater power consumption and poorer endurance, due to more voltage levels required and technology limitation. It is common to see that SLC flash is used in industrial applications, whereas MLC flash is used in commercial applications.

3. Ultra-MLC

a. Introduction

Although SLC flash is more reliable and provides better performance than MLC flash does, cost is still an issue to users. What if we could have the best of the both worlds – a new gene that delivers greater performance and endurance, but yet at the same time, is an economical solution?

The answer is yes – Ultra MLC.

The very idea with ultra MLC is that MLC flash consists of a number of fast and slow pages, and only fast pages will be used for programming when using ultra MLC. One can think of ultra MLC as an extended version of MLC flash. Table 1 and Figure 4 explain the concept of ultra MLC: The first and second bit of a memory cell corresponds to a fast and slow page, respectively, as shown in Table 1 (Left). Since we program fast pages with ultra MLC, only the bits highlighted in red in Table 2 (Middle) will be used.

MLC Flash			Ultra MLC Flash			SLC Flash
1st Bit (Fast)	2nd Bit (Slow)		1st Bit (Fast)	2nd Bit (Slow)		Bit
1	1	→	**1**	1	↔	**1**
1	0		1	0		
0	1		**0**	1		**0**
0	0		0	0		

Table 1: Cell Content for MLC (Left), Ultra MLC (Middle) and SLC (Right), Respectively

When the two bit-sets (10 and 00) from MLC flash are discarded, the bit data from ultra MLC is almost identical to that with SLC flash. In Figure 4, the threshold voltage ranges that correspond to 10 and 00 will be discarded, leaving the ones for 11 and 01. Differentiating the amount of charges inside the floating gate becomes easier, since a more separate cell distribution reduces the chance to misjudge the threshold voltage for each cell.

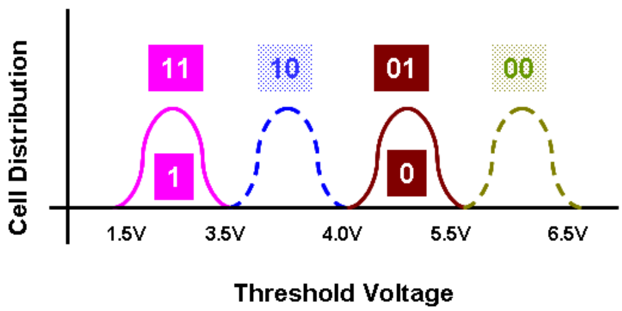

Figure 4: Cell Distribution vs. Threshold Voltage for Ultra MLC

b. Advantage(s)

Ultra MLC	
Advantage(s)	**Description(s)**
Performance enhancement	● Only fast pages are programmed with ultra MLC flash and therefore the write performance is improved. ● Please refer to "Section 4: Performance" for details.
Lifespan extension	● Based on our experiments, ultra MLC's endurance is better than that of MLC by at least 2X. ● Please refer to "Section 5: Endurance" for details.
Cost-effective solution	● The characteristics of ultra MLC are similar to that of SLC flash, but ultra MLC is a much more economical solution cost-wise.

Table 2: Major Advantages of Ultra MLC

4. Performance

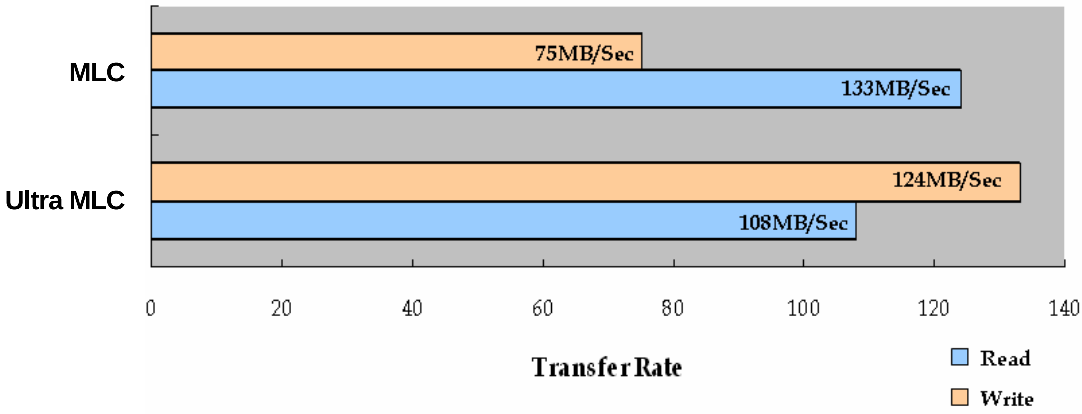

Figure 5: Read/Write Performance for CFast with PS3103

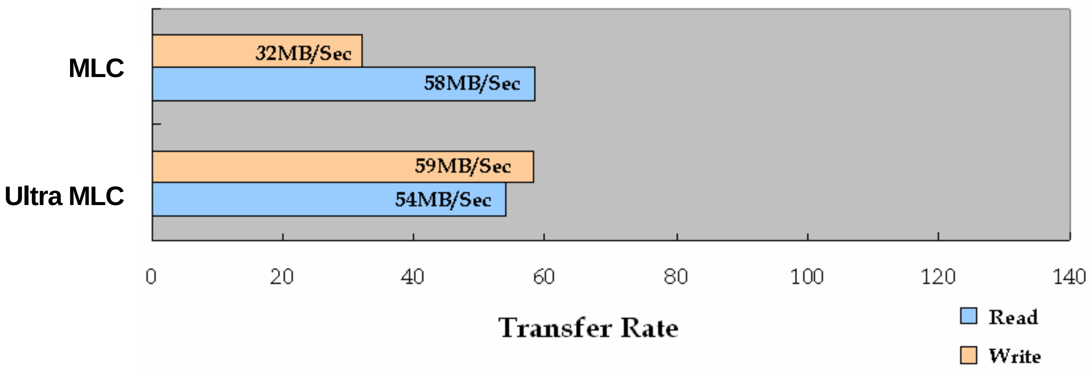

Figure 6: Read/Write Performance for CF with PS3016-P7

a. Experimental Conditions

1. CFast with PS3013

- Flash：Toshiba 43nm SK D2
- Benchmark Tool：CrystalDiskMark

2. CF with PS3016-P7

- Flash：Toshiba 56nm 4K
- Benchmark Tool：TestMetrix

b. Observations

In both cases with PATA and SATA controllers, the write performance has been tremendously improved, and the read performance with ultra MLC is also comparable to that with MLC when using PATA controller.

For CFast with PS3103, the read performance decreases with ultra MLC because each flash has two buffers inside and while the controller reads out the data from Buffer 1, the next piece of data could be "preloaded" to Buffer 2. Similarly, while the controller reads out the data from Buffer 2, the next piece of data will be "preloaded" to Buffer 1. Such an operation is also known as "cache-read". However, fast and slow pages within MLC are not arranged in an orderly fashion, so with ultra MLC, cache-read will be disabled, resulting a decrease in the read performance.

5. Endurance

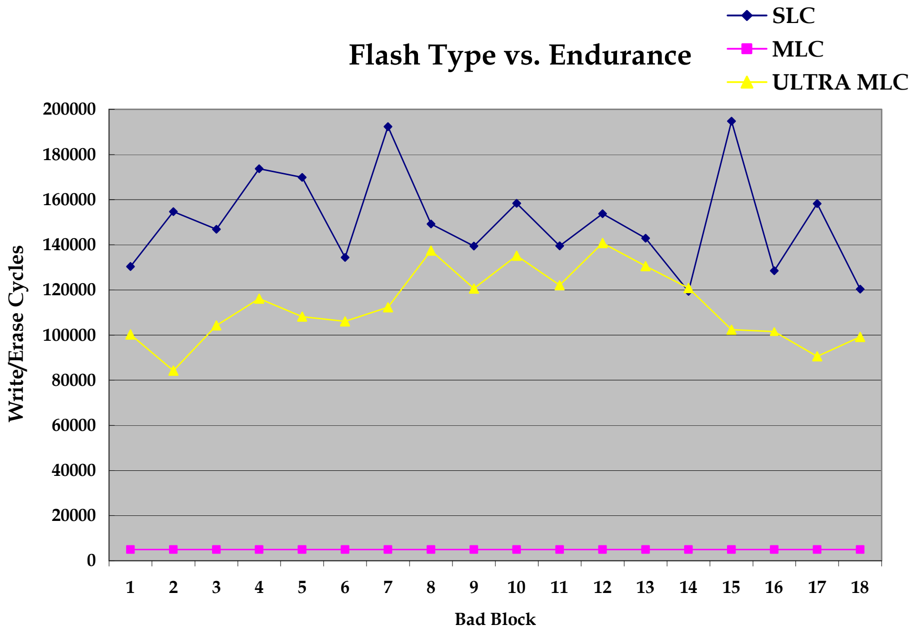

Figure 7: Endurance Comparison among SLC, MLC and Ultra MLC

a. Experimental Conditions

- SLC Flash：Toshiba 43nm 8K D2
- MLC Flash：Toshiba 43nm 8K D2
- Ultra MLC Flash：Toshiba 43nm 8K D2

b. Testing Methodology

We've proposed the following plans to retrieve endurance information regarding ultra MLC:

1. Short Term

We program and erase only one block at a time until it becomes unusable (later bad block) and then we move on to the second block so on and so for. The sampling data may not be sufficient but will be the quickest way for getting some instant results.

2. Long Term

We program and erase the entire flash over and over until all blocks become unusable (later bad blocks). This takes up about to 6 months to complete the test, and we have not yet completed the test while writing up for this paper.

c. Observations

In Figure 7, it is obvious to see that ultra MLC outperforms MLC in terms of withstanding a greater amount of usage. In general, MLC endurance is considered to be about 5K times, and our previous experiments have allowed us to conclude that endurance of ultra MLC is at least 2 times greater than that of MLC.

Appendix A displays the ECC values based on the three types of flash. Since MLC consists of four voltage levels, the chance of one bit interfering the other becomes greater, which could be translated into a higher ECC value. Therefore with MLC flash, a controller's ECC-ability needs to be more robust.

On the contrary, SLC and ultra MLC have only two voltage levels and the possibility of bit-interference becomes less, which could be observed from a lower ECC value in Appendix A.

6. Conclusion(s)

Ultra MLC, a part of the MLC family has been proved to provide better performance and greater endurance by programming only fast pages. Our experiment has shown that the read/write performance is improved with both Phison's PATA and SATA controllers. Additionally, endurance of ultra MLC is at least two times greater than that of MLC, which is used by programming both fast and slow pages. We believe that ultra MLC is the most economical alternative for NAND flash applications.

Appendix A

SLC			MLC			Ultra MLC		
Endurance	Max ECC	Failure Type	Endurance	Max ECC	Failure Type	Endurance	Max ECC	Failure Type
130420	0	Erase Fail	31132	10	Erase Fail	100261	0	Erase Fail
154682	0	Erase Fail	61588	18	Erase Fail	84238	0	Erase Fail
146872	0	Erase Fail	52286	9	Erase Fail	104283	0	Erase Fail
173730	0	Erase Fail	63206	19	Erase Fail	116143	0	Erase Fail
169906	0	Erase Fail	56847	15	Erase Fail	108135	0	Erase Fail
134393	0	Erase Fail	54888	14	Erase Fail	106080	0	Erase Fail
192340	0	Erase Fail	52543	10	Erase Fail	112328	0	Erase Fail
149203	0	Erase Fail	60782	17	Erase Fail	137423	0	Erase Fail
139485	0	Erase Fail	58269	12	Erase Fail	120583	0	Erase Fail
158384	0	Erase Fail	60128	9	Erase Fail	135190	0	Erase Fail
139575	0	Erase Fail	50923	8	Erase Fail	122059	0	Erase Fail
153753	0	Erase Fail	39572	19	Erase Fail	140787	0	Erase Fail
142934	0	Erase Fail	51206	14	Erase Fail	130579	0	Erase Fail
119374	1	Erase Fail	62755	13	Erase Fail	120857	0	Erase Fail
194743	0	Erase Fail	39284	11	Erase Fail	102394	1	Erase Fail
128475	0	Erase Fail	42756	9	Erase Fail	101495	0	Erase Fail
158222	0	Erase Fail	52931	14	Erase Fail	90572	0	Erase Fail
120384	0	Erase Fail	30845	21	Erase Fail	99184	0	Erase Fail